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UNITED STATES DEPARTMENT OF THE INTERIOR

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UNITED STATES DEPARTMENT OF THE INTERIOR
Donald Paul Hodel, Secretary

BUREAU OF MINES
David S. Brown, Acting Director

As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural resources. This includes fostering the wisest use of our land and water resources, protecting our fish and wildlife, preserving the environment and cultural values of our national parks and historical places, and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to assure that their development is in the best interests of all our people. The Department also has a major responsibility for American Indian reservation communities and for people who live in island territories under U.S. administration.

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

ft	foot	MMst	million short tons
ft^2	square foot	MM$	million dollars
gal	gallon	MMlb	million pounds
h	hour	Mst	thousand short tons
in	inch	oz	ounce
L	liter	pct	percent
lb	pound	pct/yr	percent per year
lb/ft	pound per foot	st	short ton
min	minute	yr	year

THE IMPACT OF ADVANCED MATERIALS ON CONVENTIONAL NONFUEL MINERAL MARKETS: SELECTED FORECASTS FOR 1990-2000

By Ronald F. Balazik[1] and Barry W. Klein[2]

ABSTRACT

The introduction of "high-tech" materials such as new polymer composites presents significant competitive challenges and opportunities in conventional mineral markets. Moreover, rapid advances in materials science are critical to the resolution of important economic and strategic issues, including national competitiveness and import dependence. This Bureau of Mines study examines the displacement of conventional nonfuel mineral materials by certain new materials, specifically advanced plastics and ceramics. Analyses of substitution by plastics are conducted for five major U.S. industrial sectors: motor vehicle manufacturing, aerospace applications, building and construction, packaging, and heavy machinery production. Based on interviews with more than 60 scientists, executives, and other professionals engaged in materials development and sales, forecasts of substitution by plastics during the 1990's are made for aluminum, steel, and glass. In addition to these forecasts, study findings identify key factors that will influence the emergence of advanced materials in the next decade.

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INTRODUCTION

The United States is facing dramatic changes in materials development and use. New "high-tech" materials, such as advanced plastics and ceramics,[3] are winning markets that traditionally have been dominated by conventional nonfuel mineral materials, particularly metals and glass. This competition presents unique challenges and opportunities for the nonfuel minerals industry as well as implications for national materials policy.

The past decade has been quite extraordinary for materials science. Advanced computers, powerful mathematical models, and more precise analytical tools have enabled scientists to examine and control properties of materials as never before. Moreover, stringent design and performance requirements by manufacturers of sophisticated products in highly competitive world markets have driven greater demands for new, improved materials. A 1986 review (*41*)[4] stated—

> Some of the mining industry's metal development associations have recognised this change but they receive little support from the industry itself. It is up to the miner/refiner to test and confirm that a particular metal and/or alloy is the right material for an application. If the mining industry is to succeed in the next decade, it is essential that we recognise that we are in the "materials business."

Growth of the knowledge and information sector has combined with technological change to enhance materials science far beyond its status of just a few years ago (*61*).

Traditionally, materials needs have been met by adapting existing natural substances. Now, entirely new synthetic materials are created by rebuilding their molecular structures. The creation of new materials atom-by-atom is a significant departure from the conventional sequence of extraction, purification, and combination.

In summary, modern materials science is characterized by three features that distinguish it from the past. First, new materials are being developed at a more rapid pace; technology and competitive pressures are accelerating the substitution process. Second, by working at the molecular level, scientists now can create new materials for specific properties and uses rather than modifying existing materials; parts are redesigned and manufacturing processes are changed to accommodate the new material. Third, materials development now requires a much wider range of expertise and scientific knowledge; plant design engineers and assembly line specialists must work with materials scientists to reduce total product costs.

These developments in materials science have led to the advent of remarkable new substances that are challenging standard materials in many of the latter's traditional markets. Conventional nonfuel mineral materials, especially metals, are bearing the brunt of competition from several advanced materials, particularly reinforced plastics and optical fiber. Light and durable plastics and polymer composites are substituting for metals and glass in the motor vehicle, aerospace, and packaging industries. Optical fiber may one day supplant copper as the premier medium used in telecommunications, and electrically conductive plastics now under development eventually may displace metal wire in electronic circuits (*20*). In addition, advanced ceramics are being developed for high-temperature environments that previously were the sole domain of metal alloys. The impact of such developments will grow substantially over the next decade.

Despite the broad challenge from new materials, examination of their competitiveness with nonfuel minerals to date has been limited to several studies focused on a few individual commodities or industry sectors. Among the most prominent of these studies are Department of Commerce assessments of the advanced ceramics, fiber optics, and polymer composite industries (*65-67*); however, except for the competition between optical fiber and copper, these government studies are not concerned with effects on conventional mineral-based materials.

OBJECTIVE OF STUDY

This study has a twofold objective. First, this report is intended to forecast the substitution of conventional metals and glass by new plastic materials in major U.S. industrial sectors during the 1990's. Second, this report identifies key factors expected to influence the emergence of advanced materials in new markets over the next decade. The substitution of aluminum, steel, and glass by plastics is forecast for domestic motor vehicle manufacturing, aerospace applications, building and construction, packaging, and heavy machinery and equipment production. In addition, the impact of advanced ceramics on metal demand in the motor vehicle and aerospace sectors is examined.

STUDY METHODOLOGY

Much of the information in this report is based on interviews with more than 60 scientists and officials in industry and Government that have direct knowledge of new materials development and marketing. The interviews encompassed corporate and Government professionals ranging from high-level executives and research directors to laboratory personnel, engineers, information specialists, marketing analysts, plant chiefs, distributors, retailers, and trade association representatives. The private sector interviews covered new materials producers and companies operating in markets that consume large amounts of nonfuel mineral materials (e.g., automobile manufacturing, construction, aerospace industries). Government interviews included staff members of Federal agencies in the Department of Defense, Department of Commerce, and Department of Energy. Detailed notes documenting all of the interviews are on file with the authors.

The interviews, supplemented by a literature search, were used to forecast trends in substitution during the 1990's and the year 2000. Forecasts were made for the entire plastics industry and for five major industrial

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[3]See appendix for definitions and background descriptions of the specific advanced materials examined in this report.

[4]Italic numbers in parentheses refer to items in the list of references preceding the appendix.

sectors: motor vehicle manufacturing, aerospace, building and construction, packaging, and heavy machinery production.

Interviews, rather than a review of the literature, are the basis of this study for two reasons: First, the interviews provided more information on factors affecting market trends and future relationships between new materials and their competitors. Second, the interviews provided information on the latest developments in materials innovation and market entry that had not yet appeared in the literature. Thus, interviews were viewed by the authors as the better method for eliciting the most current and appropriate information needed for this report.

Essentially, the interviews for this study were designed to (1) identify trends in new materials development or substitution, and (2) determine what factors influenced these trends. An average of 12 informed sources were interviewed for each of the 5 industrial sectors cited above. The judgment of these sources regarding both trends and influencing factors were discussed with them and compared with those of their peers. Interviewees were questioned about any differences beetween their forecasts and others. Where differences could not be reconciled or a consensus was not achieved, a forecast range is presented.

Except where indicated otherwise, the forecasts herein are intended to show only the minimum amounts of nonfuel minerals expected to be replaced by new materials. The estimates of substitution are conservative because (1) data were not available for calculating replacement in all markets where new materials are competing, (2) when there was uncertainty about what materials were competing (e.g., plastics against wood or steel in furniture), the market in question was not forecast, (3) conservative substitution rates were deliberately used in calculating trends to offset any excessive claims by new materials producers, and (4) new, more competitive materials are being developed at a pace which may exceed that of improvements in conventional materials. More details on substitution calculations are provided for each industry in the "Industry Analyses and Forecasts" section.

One caveat must be made regarding the interview methodology: the opinions expressed by the interviewees represent their personal, subjective assessments of current and future events. Nevertheless, their judgments were the considered views of professionals with many years of experience and responsibility in materials design and marketing. Moreover, the authors have tried to present the rationale given for forecasts and have attempted to show the full range of different projections obtained from the interviews. Thus, readers can judge for themselves the plausibility of the projections presented.

ACKNOWLEDGMENTS

The authors wish to thank the many industry and Government professionals cited in this report for their valuable information used to develop substitution forecasts. In particular, the authors would like to extend their appreciation to several Bureau of Mines employees including Frederick Schottman, physical scientist, Division of Ferrous Metals, Washington, DC (steel estimates); Louis Sousa, economist, Division of Minerals Policy and Analysis, Washington, DC (materials technology assessment); and Murray Schwartz, Manager of Materials Research, Division of Materials and Recycling Technology, Washington, DC (advanced ceramics forecast evaluations).

The authors also wish to acknowledge the assistance of several individuals who provided valuable technical data for particular materials and industries. These persons include Jerry Fanucci (aerospace materials), R. Nathan Katz (advanced ceramics), and Jerome Persh (aerospace industry); these Department of Defense materials engineering personnel are located respectively at the Army Natick Laboratory, Natick, MA; the Army Materials Technology Laboratory, Watertown, MA; and the Office of Research and Engineering, the Pentagon. In addition, the authors also wish to thank David Cole, assistant professor, University of Michigan, Ann Arbor, MI, for his assistance on motor vehicle forecasting, and Roy Sjoberg, materials manager, Chrysler Corp., Detroit, MI, for his assessment of composite materials in automobiles.

INDUSTRY ANALYSES AND FORECASTS

This section contains separate analyses of substitution by plastics in five major U.S. industrial sectors: motor vehicle manufacturing, aerospace applications, building and construction, packaging, and heavy machinery and equipment production. The analyses include substitution forecasts and discuss conditions that will influence this substitution in the 1990's.

MOTOR VEHICLE MANUFACTURING

Plastics

Car and truck manufacturing represents the largest potential domestic market for high-performance plastics because the industry produces a great number of motor

vehicles[5] that could incorporate sizable quantities of these materials. Approximately 10 million U.S. automobiles and trucks are expected to be built in 1990 (*8*). Thus even a small increase in plastics used per car or truck translates into a large total increase in plastics consumed by the motor vehicle industry.

Table 1 indicates the amount of plastics substituting for steel in the manufacture of U.S. automobiles during 1985 and forecasts displacement of steel by plastics for motor vehicle production in 1990 and 2000. These forecast quantities are based on interviews and documents that project the level of car and truck production, the average weight of the vehicles, and the share of each vehicle accounted for by plastics and steel. Note that "downsizing" of vehicles accounts for some of the declines shown for steel but does not appear significant enough to cause all of the decrease. This is compatible with interview comments that plastics will replace metals for many uses in the domestic motor vehicle industry.

Table 1.—Substitution by plastics in U.S. motor vehicle manufacturing: 1985, 1990, and 2000[1]

Vehicle type	Steel displaced by plastics, MMst		
	1985	1990	2000
Automobiles and vans	1.3	1.6-2.2	2.5-7.1
Compact and light pickup trucks	NA	.18	.23

NA Not available.
[1]See "Forecast computations" section for calculations used to derive these data.

Plastics use grew significantly in U.S. motor vehicle manufacturing during the past 10 yr, but further growth will not be dramatic until the 1990's. This is consistent with auto industry officials' forecasts that plastic outer body panels or "skins" for cars will not be used in significant quantities until the early 1990's. Currently only GM's Pontiac Fiero and Chevrolet Corvette have plastic (fiberglass) skins, and both of these are low-production-model cars. In 1989, several GM cars are expected to have plastic fenders, rocker panels, and grille opening panels, i.e., partially plastic skins (*28*). Plastic have the advantage of lighter weight and superior corrosion resistance, which even two-sided galvanized steel may not match in performance.

Use of additional plastics under the hood (some plastics are already being used for such parts as radiator headers and master hydraulic cylinder reservoirs) is expected to trail their use for outer body panels for several reasons. To design and manufacture firewalls, floor pans, and sidewalls with plastics rather than metal requires composite materials that have high-temperature resistance, low flammability, etc. These relatively expensive materials are closer to aircraft composites than to car skin composites in both performance and cost. Plastics manufacturers (Du Pont, General Electric, Celanese) must reduce costs before composites can replace metal in under-the-hood, high-temperature applications. In addition to high costs, the threat of liability lawsuits from using "plastic parts", perceived as inferior by much of the public, has been an impediment more difficult to overcome than some of the technical performance problems faced. (As will be discussed below, this liability-lawsuit threat has also been a serious obstacle to increased composites use in aircraft, especially passenger airliners.)

[5]The term, "motor vehicles," in this report refers to automobiles, vans, and light (pickup) trucks; "automobiles," as used here, includes vans.

Excluding the engine block, which will remain predominantly metal into the 21st century,[6] the frame and other structural parts area is probably the last area where plastics will substitute for metal. Not only are expensive composites (closer to aircraft composites in performance and cost) needed for strength, but there is a major problem to be solved in joining plastic (composite) frame parts together. Currently the only chassis parts made of composites are graphite-epoxy leaf springs in the Chevrolet Corvette. However, fiber-reinforced plastic wheels, which are 20 percent lighter than aluminum wheels, are now being marketed (*19*). Although two graphite-reinforced drive shafts are being tested on vehicles experimentally, metal drive shafts are expected to be used for many years.

The following factors will affect the amount of plastics used per car:

1. *The costs of both the plastics and the steel that they replace, and in addition the cost of other materials, such as aluminum and magnesium, that compete with plastics in replacing steel.*—For outer body panels, galvanized sheet steel is $0.44 per pound and composites are $1.20 to $1.50 per pound.

2. *The cost of designing and manufacturing plastic car parts versus steel, aluminum, or in a few cases, magnesium car parts.*—Determining this cost involves several interrelated considerations. Tooling costs are considerably higher for producing metal parts than plastic parts. However, this higher initial cost can be offset given a sufficiently long production run, since the metal parts production rate may be 16 times faster than the plastic (fiberglass) parts production rate (500 metal parts versus 30 plastic parts per hour). Thus 1 million units of one fender type (long production run) favors metals, whereas 250,000 favors plastics. The break-even point in metal versus plastic car part costs reportedly is 300,000 to 500,000 units (but closer to 500,000) of one part type. In addition, although low production runs increase overhead per part, plastic parts reduce overall labor costs and/or assembly time because several (and in some cases many) metal parts often can be replaced by one integrated plastic part. Given these factors, one car company official said that if the plastic part production rate can be doubled to 60 parts per hour, plastics can be competitive with steel despite being much more expensive than steel. The deciding variable may then be the length of the production run, and the expected trend toward shorter production runs for many car models would favor plastics. Needless to say, steel companies are aware of the serious threat plastics pose in the automotive market, and the steel industry is making more capital investment in electrolytic galvanized high-strength steel production in response to this competition (*31*).

3. *The prices of oil and gasoline.*—Higher oil and gasoline prices would increase demand for, and lead to increased production of, lighter weight, more fuel-efficient cars that contain additional weight-saving plastics. However, this trend would be partly offset by higher plastics prices, reflecting higher oil-based plastic feedstock prices.

4. *The ability of plastics to meet high-performance requirements (high-temperature resistance and/or high strength) for under-the-hood and frame parts, which is a safety issue as well.*

5. *Changing consumer tastes and preferences.*

[6]However, Amoco and Polimotor are testing a plastic V6 engine with metal lining the pistons and other high-wear surfaces (*19*).

6. The economic feasibility of recycling automotive plastics.—The inability to recycle plastics profitably could seriously restrict their use in motor vehicles since millions of "junk" autos in need of recycling are generated each year.

A few additional comments about plastics use in cars should be made. First, additional plastics use in cars will coincide with the introduction of new car models, where retooling would be necessary in any case, even if the parts continued to be made of metal. Second, as a materials research scientist specializing in composites stated, *thermoplastics,* as opposed to *thermosetting composites* (see the appendix definitions), may represent the only serious competition to metals in cars because the composites production rate is too slow for automobile production rates. This is consistent with the above statement by an auto industry official that *if* the plastic part production rate were doubled, then plastics would be competitive with steel. Third, car company officials express some concern that, unlike steel, which represents a secure source of raw material for motor vehicles, plastics, being oil-based, are vulnerable to oil shortages, such as occurred in the 1970's when the U.S. was more dependent on OPEC oil.

In conclusion, the wide forecast range for substitution by plastics in the 1990's within the motor vehicle industry (table 1) reflects uncertainties regarding the interaction of all the complex factors described above.

Ceramics

The thermal strength and hardness properties of advanced ceramics have given these materials significant potential for application in car and truck engines. However, ceramic coatings and parts are just beginning to be introduced by the motor vehicle industry and will not seriously compete with conventional materials in this sector for a decade or more.

The most near-term uses likely for advanced ceramics are items such as turbocharger rotors, piston rings and pistons, cylinder liners, and small stationary parts (*65*). Coatings and smaller parts will be introduced first. Currently, the Nissan 300 ZX has engineering ceramics in the turbocharger (*55*), and Isuzu has small engine components containing ceramics. Wear-resistant ceramic seals in engine water pumps are already widely used on a commercial scale. The U.S. Army is testing a Cummins diesel engine truck that has a ceramic-insulated cast iron (engine) block. Kyocera Corp. of Japan has built a prototype diesel engine with ceramic pistons, cylinders, and heads; it is claimed that the engine, which needs no cooling system, can operate for 500,000 miles (*19*). One U.S. auto executive predicted that by 1997 ceramics would be used in high-heat areas of the power train, such as the turbocharger, in domestic cars.

In general, the outlook is for ceramic parts or ceramic-coated metal parts to be introduced gradually into high-heat areas of motor vehicle engines. Ceramics for insulation, coatings, and small engine parts are expected to be introduced in at least one U.S. diesel truck line and in some Japanese cars during the early 1990's (*33*).

Engines with ceramic blocks as well as small ceramic parts are being tested and demonstrated both in Japan and the United States but will not be commercially feasible until early in the next century.[7] Although engineered structural ceramics can withstand very high temperatures, they are subject to catastrophic failure (extensive fracture) because of their brittleness. Much research remains to be conducted on advanced ceramics to reduce the chance of catastrophic failure. Well beyond year 2000, lightweight ceramic engines (compared to cast iron engines) may be produced that reduce the weight of the motor vehicle further by operating at high, fuel-efficient temperatures with no radiators.

Forecast Computations

For each forecast year, the expected average weights (*28, 40, 45, 74-75*) of both domestically produced cars and light trucks were multiplied by estimated production levels (*8, 22, 27, 43*) of these vehicles and combined with the predicted percentage of plastics in the individual vehicles produced (*16, 27, 40, 43, 45, 56, 64, 75*). For example, estimates of domestic car production (7.4 million units), average new car weight (2,150 lb), and plastic component of car weight (20 pct) were combined to indicate the lower end of the total plastics used (3.2 billion lb) for U.S. automobile production in 2000. Such calculations were performed separately for automobiles and vans and for light trucks because the weight, production levels, and shares of material per vehicle varied considerably between these two categories. Forecast ranges, rather than a single predicted amount, are used where differences among sources could not be reconciled.

The quantities of steel replaced by plastics in a given forecast year were derived for table 1 by multiplying the amount of plastics calculated above by a factor of 1.6, which is considered a conservative steel-to-plastic weight ratio for materials used in the industry (*21, 57*). Information used to compile table 1 indicates that the amount of steel used per vehicle will decline more sharply than average vehicle size during the forecast period. Thus, the predicted decrease in demand for steel must be attributed to more than the production of smaller vehicles. The use of more plastics in car and truck manufacturing is considered to be the primary cause of the decrease beyond "downsizing," although the use of other substitutes (e.g., aluminum, high-strength steels) is a contributing factor.

AEROSPACE INDUSTRY

This discussion is focused almost entirely on aircraft manufacturing, which is by far the largest materials-consuming part of the aerospace industry,[8] and the sector for which most information is obtainable. The two primary categories of aircraft are civilian and military. Civilian aircraft include passenger airliners (e.g., Boeing and McDonnel Douglas), general aviation (smaller business, personal, and utility aircraft such as Cessna, Beech, and Piper), and helicopters. Of the dozen military aircraft types, major categories include fighters, bombers, attack,

[7]One source, however, has indicated that automotive engines built entirely of ceramics could be a commercial reality in the early 1990's. In any case, if engines made of ceramics are standardized and put into mass production, the demand for these materials would easily surpass all other uses combined.

[8]The aerospace industry consists of aircraft, guided missiles, and space vehicles (including engines, equipment, and parts needed for these craft.) Industry shipments totalled $97 billion in 1986 (*34*).

and cargo-transport. In recent years, the number of civilian aircraft shipped has been as much as three times that of the military, yet the value of military aircraft shipments has been double that of civilian aircraft.

Aircraft are divided into three general components for purposes of discussion: the airframe, the engine(s), and the avionics (aviation electronic devices and equipment). The airframe can be further divided into primary structures such as wings and fuselage, the failure of which could result in the plane crashing, and secondary structures (doors, flaps, slats) that are less important to aircraft safety. Between these categories is the empennage or tail assembly, which can sustain some damage and still enable the aircraft to land. (The tail assembly consists of vertical and horizontal stabilizers, including the fin, rudder, and elevators.)

Aircraft Composites Versus Automotive Composites

Plastic composites (see the appendix definitions), the principal materials replacing metal in aircraft manufacturing, vary considerably from those used for motor vehicles, both in their higher quality and performance and in their attendant greater cost. For example, aircraft fiberglass, made with high-strength S-glass fibers, costs about $10 per pound; while fiberglass for cars and boats, made with weaker E-glass fibers, costs about $1.50 per pound. Similarly, aircraft graphite-epoxy is made of high-strength graphite fibers tightly woven into cloth and costs $20 to $50 per pound, while lower strength and/or lower quality unwoven graphite fiber-epoxy for boats and cars costs a fraction of this price. Other "plastic" aircraft composites include Du Pont aramid fiber Kevlar-epoxy at $10 to $25 per pound, high-temperature-resistant bismaleimide at $75 per pound, and thermoplastics with glass reinforcing fibers, which are expensive but have no established market prices as yet. (These thermoplastics are more expensive than graphite, but their prices are anticipated to come down through economies of scale when they are produced in large quantities.) As may be expected, the higher prices of aircraft composites reflect the greater labor and longer times needed (compared to car composites) at each stage of processing and/or manufacturing. For example, not only does tightly woven graphite cloth take longer to make than unwoven graphite fibers, but the curing process for graphite-epoxy aircraft parts takes from a minimum of 2 h to as long as 10 h (counting an 8-h post cure) compared with 15 min for graphite-epoxy car parts.

The lower production rate of aircraft versus motor vehicles permits greater use of longer cure composites in aircraft manufacturing. The much higher prices of, and much longer processing times permitted for, aircraft composites allow for their far greater variety vis-a-vis motor vehicle composites. It is in the aerospace sector that new state-of-the-art composites will be developed, rather than in the motor vehicles sector where the goal is largely to increase the plastic parts production rate and reduce the cost of already existing plastics.

Costs of Composites and Metal in Aircraft

Overall composite costs are similar to those of metal for aircraft. Initially the composites are more expensive than the metal they replace, but these higher material costs are offset by savings in fabrication and assembly costs. In fabrication, composites, unlike aluminum, require no machining. An example will illustrate assembly cost savings. A particular metal helicopter requires 11,000 rivets (as fasteners). The cost of machining the rivet, drilling and inspecting the hole, installing the rivet, and rechecking after installation is $10 per rivet. By contrast, the composites used to build the helicopter can be glued together (with epoxy) for one-tenth the cost. (In this latter case only a small number of mechanical fasteners are needed.)

Advantages of Composites

Composites such as graphite-epoxies have several advantages over the aluminum they replace in the airframe. Probably the most significant of these is the lighter weight of composites: aluminum parts generally weigh about 1.3 times as much as the composites that substitute for them. The lighter weight enables the aircraft to have a longer range and/or bigger payload, and increased maneuverability and/or speed. In some cases composites also have higher strength than aluminum, which can also improve maneuverability. For military aircraft, longer range and/or bigger payload and greater maneuverability and/or speed are considered crucial; for civilian aircraft, the main advantage is the increased fuel efficiency, i.e., lower operating cost, which is expected to offset the higher prices of composite parts compared with aluminum. Other advantages include savings in fabrication and asssembly costs.

Use of Composites in Airframe

Relatively little experience in the use of composites compared with metals in aircraft means that composites will initially be used mainly in secondary structures, i.e., doors, flaps, slats, and part of the tail. As experience is gained in their use, composites will gradually be incorporated into more primary structures.

Passenger airliners are just beginning to incorporate composites into their airframes. Although Boeing 757 and 767 aircraft are said to make "extensive" use of composites, such materials comprise less than 5 pct of their airframes; it is extensive use, therefore, only in a relative sense, i.e., previous passenger airliners had almost no composites.

There are numerous reasons, in addition to relative lack of experience, why, despite their advantages, composites will only slowly be introduced into aircraft, especially into passenger airliners. The passenger airliner manufacturers have huge investments in metalworking machinery and equipment; therefore, they would prefer to use this machinery as long as it will last, i.e., 20-plus years (in airliner manufacture). Also, these companies do not want to risk a hasty conversion to composites in case some problem in their use that has not revealed itself in the short or medium term emerges in the long run. In addition, advances such as aluminum-lithium alloys, which are 10 pct lighter in weight than aluminum, extend the time in which metals can compete with composites.

In manufacturing military aircraft, unlike passenger airliners, the companies are reimbursed for the cost of machinery to make composite parts under military contract. Reflecting this, the military has been quicker to introduce composites into aircraft where performance is

given a higher priority than costs, and passenger airliners have trailed behind because of cost constraints. Another factor contributing to the more rapid adoption of composite parts by the military is that the certification and approval of each new aircraft part (after undergoing testing) by the Federal Aviation Administration (responsible for civilian aircraft certification) is a much slower process than is the military system of certification.

Several managers and scientists in the aerospace field have indicated that the largest impediment to use of composites in passenger airliners is not of a technical nature, but rather the threat of liability; i.e., lawyers for plaintiffs in plane-crash lawsuits could call the composites "plastic parts," capitalizing on the image of inferiority that plastics may have among the public.

Differences between military and private sector aircraft manufacturing regarding the certification, reimbursement, and liability factors discussed above contribute to the greater use of composites in fighter and attack planes. In contrast to the very small percentage of composites in a passenger airliner (less than 5 pct of the airframe weight), military aircraft airframes average 10 to 15 pct composites (*44*), and one aircraft, the AV-8B (the second generation of the British Harrier "jump jet"), already incorporates 26 pct composites (mainly graphite-epoxy) (*66*). The composites' share of airframe weight in military aircraft is forecast to average 25 pct within 5 to 10 yr (*44*), the advanced tactical fighter (ATF) in the mid-1990's will have 50 pct composites, and some designs of future military aircraft would use as much as 60-pct-composite airframes (*21*). Estimates of the extent to which composites will substitute for aluminum in military aircraft range from 20 to 70 pct of the airframe weight (*32*). This wide range reflects the high degree of uncertainty in predicting future technological developments for composites, their costs, and their acceptance, and in foreseeing long-term problems, if any, that may develop with composites.[9]

Beyond the year 2000, it is forecast that the next generation fighter plane (i.e., the generation after the ATF) will have a 100-pct-composite airframe, except for metal landing gear struts (*29*).

On the other hand, composites use for bombers and cargo-transport aircraft trails far behind that for fighter and attack aircraft. For example, the B-1B bomber's airframe is less than 5 pct composites, one reason being that it was designed 15 yr ago. Similarly the C5-B Galaxy (replacing the C5-A), which is one of the world's largest transports, is almost all metal (airframe). Also, the C17 or C18, which will replace the C130 Hercules transport, was originally designed with no composites, but now will incorporate small amounts of composites in the secondary structure.

In summary, the percentage by weight of the military airframe made of composites averages more than twice that of civilian airframes.[10] For the many reasons cited above, military aircraft can be expected to continue to lead civilian aircraft in the use of composites.

[9]It should be noted, however, that the first military application of composites was boron-epoxy used in the tail of the F-14 fighter in 1971, and there has been no problem of the material degrading. (Boron is no longer used in aircraft because it is difficult to work with and more costly than graphite.)

[10]One exception is Beech Aircraft's new Starship (general aviation airplane), which has a 100-pct-composite structure except for metal landing gear struts and engine. However, this one model represents a very small fracton of all general aviation planes, and these, in turn, are a small share of the total civilian aircraft value, most of which is accounted for by passenger airliners.

Use of Composites and Ceramics in Jet Engines

Unlike the airframe, where composites have already substituted for aluminum in sizable quantities (at least on some military aircraft), the engine area presents technical and/or performance problems more difficult for composites to overcome. The high-temperature environment of jet engines prevents the use of composites such as graphite-epoxy (which can withstand temperatures of 350° F) because the high heat causes layers of the composite to separate, i.e, become unglued. The problem is compounded because this damage usually is undetectable on the airplane and can only be seen through laboratory examination. (Thermoplastics are more damage-tolerant than epoxy composites, but they too cannot withstand the high temperatures.) However, bismaleimide resin, which can withstand at least 450° F and possibly as high as 600° F, is an advanced engineering plastic that replaces titanium in some of the latter's relatively high-temperature engine applications noted below. A specific example of bismaleimide's use is in the AV-8B Harrier jump jet's tilt nozzles used for hovering.

For jet aircraft engines, titanium rather than aluminum is used for structures around engines, air ducts, and less intense heat applications in engines. Nickel- and cobalt-base superalloys (made from nickel, cobalt, chromium, molybdenum, columbium, and tantalum) are used in the hottest sections, such as the turbine blades. Not only can these metals (especially the superalloys) withstand much higher temperatures than currently developed composites, but also, unlike damage to composites, metals cracking or fracturing is generally detectable on the airplane in advance of failure.

Turning to engineered ceramics, it is expected that with the exception of their possible use as coatings, ceramics will not be used in jet aircraft engines until well into the next century. Unlike plastic-matrix composites, engineered ceramics retain strength at very high temperatures. However, they also are subject to catastrophic failure because of their brittleness. With the current state of technology, this characteristic of sudden, virtually total fracture means that ceramic engine parts pose an unacceptable risk of engine failure and resultant loss of life. One possible answer to this problem is ceramic coatings of superalloy metal parts, where the structural integrity of the part is ensured by the underlying metal should the coating fail. Ceramic parts will be used in stationary and unmanned gas turbines and in drones and missiles where their failure would not result in loss of life. These uses will provide significant experience for more high-risk applications.

Although advanced ceramics are not expected to be used in jet aircraft engines until well beyond the year 2000, they offer advantages that almost ensure their eventual use. Engineered ceramics, like polymer composites, are lighter in weight than the metal they replace. Turbine blades composed of ceramics (instead of superalloys) can be made lighter in weight, which in turn means the turbine blades will be connected to a smaller, lighter shaft, and smaller (and lighter) bearings will suffice, etc. Thus, there is a "cascading benefit," or spillover effect, in that the lighter weight of one group of parts (turbine blades) permits use of other smaller, lighter parts (shaft, bearings, etc.), resulting in a total weight savings of several times the initial decline in weight from using ceramic turbine blades. In addition to their light weight, advanced engineering ceramics have other desir-

able physical and chemical properties, including resistance to heat, wear, and corrosion.

In conclusion, jet aircraft engines are the last bastion of metals, i.e., the last area where metals will be replaced by, in this case, engineering ceramics. For ceramics to be used in this application, they must be made much tougher, i.e., they must be able to absorb much more energy before fracturing. Technological advances to achieve this greatly increased reliability may require many years of research.

Highest Performance Composites

There are several types of composites that represent the leading edge of materials technology. These categories of materials, some of which are relatively expensive, include ceramic reinforcement-metal matrix composites, carbon fiber-metal matrix composites, and carbon fiber-carbon matrix composites. An example of the first type is silicon carbide particle-metal matrix composites, which are lighter in weight than the almost 100-pct-pure metals they replace, are heat-resistant, have good thermal stability (i.e., little expansion or contraction), and cost somewhat over $10 per pound. An example of the second type (and at the other end of the cost scale) is a carbon fiber-aluminum-magnesium matrix costing thousands of dollars per pound and used in the space program where weight savings more than make up for the cost of the material. One such carbon-metal composite for optical and communications use in the space program has superior thermal stability, costs as much as $50,000 per pound, and represents the frontier of materials technology. The third type, carbon-carbon composites, like engineering ceramics, can withstand extremely high temperatures. However, unlike ceramics, they oxidize in an environment such as a jet engine. Work is underway on developing protective coatings for these materials, but it is expected to be at least 5 yr before suitable coatings are produced (*44*).

In conclusion, some metal matrix composites represent state-of-the-art technology, and these composites offer opportunities for metallic minerals to regain markets previously lost, if not develop new ones. Of course, the metal consumed per unit of product generally is less for metal composites than for virtually pure metals.

Forecast Computations

Calculations based on data collected for this report indicate that, for passenger airliner manufacturing, only 500 st of aluminum was displaced by plastic materials (essentially polymer composites) in 1985. This amount accounted for less than 5 pct of the aluminum used in the airframes of these craft. However, at least 4,000 to 11,000 st of aluminum, accounting for 20 to 60 pct of consumption for airframes, is expected to be replaced by plastics in airliners for any given year in the 1990's. The procedures followed to calculate this substitution are described below. Note that the substitution estimates are limited to passenger airliner manufacturing, which may account for only one-third of all materials consumed in the aerospace industry. The preceding discussion of the industry provides information on current materials substitution in many areas beyond the airliner sector. However, some data needed to estimate future military, missile, and space programs are highly classified and therefore are not available for a forecast. Nevertheless, in view of the foregoing industry discussion, it is not unreasonable to expect these sectors to easily exceed the pace of substitution predicted for passenger airliner production.[11]

For the 1985 airliner estimate given above, the combined weight (*1, 35*) of every type of passenger airliner manufactured in that year was identified and multiplied by 0.7[12] to obtain the total airframe weight produced. This total was then multiplied by the percentage share (approximately 4 pct) of airframe weight accounted for by composites as estimated by various sources (*32, 44, 62-63, 73*). The result of these computations was multiplied by a factor of 1.3, which is the approximate weight ratio of aluminum (*21*)[13] to composites used in the aircraft industry. This final step indicates the estimated amount of aluminum currently displaced by composites in airliner manufacturing.

For the forecast covering the next decade, a 3.3-pct annual growth rate to 1990 was applied to the total 1985 airframe weight. (This increase is predicted by the Department of Commerce (*34*) for aircraft equipment, including airframe subassemblies, over the next 5 yr.[14]) The 1990's airframe weight obtained from the computation was then multiplied by the lower and upper limits (25 and 65 pct) forecast for composites as a percentage of airframe weight during that period (*32, 62, 73*). The resulting range of composite weights was then multiplied by the 1.3 weight ratio cited above to indicate the amount of aluminum that could be displaced.

BUILDING AND CONSTRUCTION

Discussion

Several businesses in the U.S. construction industry[15] that customarily have been important consumers of metal are increasing their demand for plastics. Principal among these consumers are firms that manufacture pipe and conduit, siding for buildings, and windows for residential housing. Other building trade applications in which plastics are competing with conventional mineral materials include interior and exterior moldings, doors, plumbing fixtures, and insulation (*60*).

Lighter weight, lower fabrication costs, design flexibility, and maintenance ease are features that have promoted demand for plastic in construction materials and will continue to spur its use by builders over the next decade. According to a recent report (*54*)—

> The use of plastics in construction has risen steadily since the mid-1960s, when plastic products represented only 2 percent of total

[11]Although airliner manufacturing apparently used less than 1 million lb of composites and reinforced polymers in 1985, the Society of Plastics Industry reports that the entire aerospace industry consumed 37 million lb of these materials in that year (*60*). If all of these composites have replaced aluminum, over 23,000 st of aluminum have been displaced.

[12]The airframe (described earlier) accounts for about 70 pct of airliner weight (*71*) and is that part of the craft where composites and engineering plastics are replacing metals.

[13]As noted in the preceding discussion of the industry, aluminum is virtually the sole rival of composites for the airframe.

[14]The forecast may be conservative because the Federal Aviation Administration estimates that air passenger traffic will climb at a compound annual rate of 4.5 pct through 1995 (*34*).

[15]As used here, the domestic construction industry includes all private sector building and public works programs. During 1986, private residential and nonresidential construction totaled about $280 billion, while publicly funded building (roads, bridges, etc.) reached $62 billion (*36*).

> building materials consumed. By 1981, market share had jumped 10 percent, or 6.5 billion pounds valued at $5.7 billion ... Gains will be most rapid during the 1980s, then moderate (as housing starts decline and some product markets approach saturation).

The report forecasts that exterior plastic products will exhibit the most rapid growth—over 7 pct/yr—owing to cost differentials between these products and those made of metal. Also according to the report, the consumption of plastic pipe, the strongest challenge faced by metals in construction, will reach 5.5 billion lb annually by 1995.

As shown in table 2, forecasts of substitution by plastics have been estimated for ductile iron, steel, and aluminum used to produce piping, siding, and window frames. Currently, these items account for slightly less than half of the plastics utilized by the building industry (*60*). Most of the remaining plastics for construction compete with nonmineral materials, particularly lumber and wood products.

Table 2.—Substitution by plastics in th U.S. construction industry: 1985, 1990, and 1995

Substitution	1985	1990	1995
Metal displaced by plastic pipes and conduit, MMst:			
Iron in sewer lines	1.95	NA	3.65-5.10
Steel and iron in drain, waste, and vent pipes	0.25	NA	0.34-0.43
Steel in conduit	0.29	NA	0.34-0.58
Metal displaced by vinyl siding, Mst:			
Aluminum	25.3	NA	63.6
Steel	6.7	NA	20.5
Aluminum displaced by plastic window frames ....Mst	12	24	NA

NA Not available.

Steel and ductile iron for conduit and for drain and sewer pipe account for most of the metal that is expected to be replaced by plastics in construction during the early 1990's. Most of the gains against metals will be made by plastic piping (predominantly polyvinyl chloride) within buildings and as underground water and drain lines in urban areas (*70*). Plastic pipe already accounts for over 80 pct of all rural mains laid today (replacing cast iron and vitreous clay pipe), but thus far has captured only about 40 pct of municipal markets (*70*). Delays in modification of local plumbing and building codes to permit the use of plastic have retarded conversion in these areas (*70*).

In the siding business, aluminum is the metal that faces the greatest competition from plastic (primarily vinyl) (*25*). Steel presently accounts for only 3 pct of the market, a share that is not expected to change much in the next decade (*52*). Aluminum, however, is expected to lose about 5 pct of its current market by 1995, and most of this loss can be attributed to substitution by plastics (*52*).

Aluminum also faces a strong challenge from plastics as a material used to fabricate window frames for houses and other residential structures. Currently, plastic (primarily vinyl) has a 15-pct share of the residential replacement window business and accounts for about 6 pct of the total residential window market (*17, 51*).[16] Forecasts of demand growth for plastic window frame materials range from 10 to 20 pct per year through 1990 (*46, 51*). Although aluminum is expected to remain dominant in the commercial and office building market, it is losing about 5 pct of its residential window market each year to plastics and is forecast to be a small factor there by the year 2000 (*53*).

In addition to substitution of the metals discussed above, plastics are beginning to compete with copper and glass as construction materials. Small-diameter (1-in or less) plastic pipes are being used in place of copper pressure piping within buildings and homes as fresh water lines. Building trade distributors and retail outlets contacted for this study indicate that plastics account for less than 5 pct of sales in this category but are becoming more competitive (*9, 26, 27*). In addition, transparent plastics (primarily acrylics) have penetrated some flat glass markets, but are not expected to advance much further unless their prices decrease and problems with ultraviolet light stability and abrasion resistance are overcome (*47*).

Forecast Computations

Using data from industry and government sources, the procedures described below were followed to calculate the forecasts shown in table 2.

Pipe and Conduit

Two methods of calculating substitution were used to provide a cross-check and forecast range for pipe and conduit materials. First, an estimate of total domestic pipe consumption for the construction industry in 1995 (4.0 billion ft) was obtained (*50*). The source of this estimate also indicated that plastic pipe would increase its market share to 55 pct (currently 45 pct) for all uses including construction. In addition, it was assumed that the proportions of plastic pipe used to compete against steel conduit, steel and iron drains and vents, and ductile iron sewer lines would be the same as the average for the last 5 yr for which data were available (1980-84).

By combining this information with estimated weights of plastic, steel conduit, and iron pipe (*10, 24, 37, 57-58*),the lower end of the forecast range was computed for table 2.[17] For example, 4.0 billion ft × 0.55 × 0.125 (proportion of plastic pipe used as conduit between 1980 and 1984) × 2.5 lb of steel per foot of conduit = 344,000 st of steel conduit demand replaced by plastic pipe use in 1995.

The second approach used to calculate metal pipe replacement provides the upper end of the range shown in table 2. The basis of this approach was sources that indicated that plastic pipe and fittings for construction would increase at 6 to 7 pct annually to 5.52 billion lb in 1995 (*48*). The same 1980-84 competitive proportions cited above were assumed to be constant. These data and the weights of plastic used for conduit, drain, vent, and sewer pipe then were used to calculate the lengths of plastic pipe consumed in these categories in 1995. Weights of equivalent lengths of steel conduit and iron and steel drains and sewer lines then were used to calculate the higher forecast in table 2.

Siding

Current displacement of aluminum and steel siding by vinyl siding is estimated from market share data for

[16]We estimate that residential window space accounted for 57 pct of the total window area in all buildings constructed during 1985.

[17]Weight estimates used for pipe calculations are as follows: plastic conduit, drain-vent, and sewer lines are 1.5, 2.0 and 3.5 lb/ft, respectively; steel conduit and drain-vent lines are 2.5 lb/ft and ductile iron sewer lines are 18.5 lb/ft. The steel and iron weights are based on smaller than average pipe sizes to avoid exaggerated substitution estimates.

1984, the latest information available (*72*). These data indicate the following siding market shares for that year: aluminum, 17 pct; steel, 3 pct; vinyl, 14 pct; other materials (primarily wood and asphalt), 66 pct. Thus, aluminum and steel account for 20 and 3 pct, respectively, of all nonplastic siding materials. Based on these percentages and confirmation by interview sources, it is estimated that at least 20 pct of the current plastic market once belonged to aluminum and roughly 3 pct previously was occupied by steel (*11*). These percentages of the 1984 vinyl siding market (563 million ft^2) equate to 112.6 million ft^2 of aluminum and 16.9 million ft^2 of steel. The estimated 1985 tonnages shown in table 2 are based on these figures and the quantities of aluminum or steel needed per unit area of siding produced.[18]

One source indicates that by 1995, aluminum and steel would lose an additional 5 and 1 pct of their current markets, respectively (*52*). However, plastics use is expected to increase and account for 81 pct of all market share growth by 1995 (*52*). Total siding of all materials is forecast at 4.25 billion ft^2 (*52*). Thus, 5 pct of 4.25 billion ft^2 multiplied by 0.81 was used to indicate the additional amount of aluminum siding that would be lost in competition with plastic by 1995. Substitution for steel was calculated in a like manner.

Windows

The forecast substitution of aluminum by plastic for windows uses the following data obtained from industry sources: (1) Total number of aluminum residential windows (19 million) installed in 1985 (*17*); (2) number of plastic-frame windows (2 million) replacing aluminum windows in 1985, with annual growth rate (15 pct minimum) of the former to 1990 (*13, 46, 51, 53*); and (3) amount of metal (12 to 15 lb) in aluminum residential windows (*17*). With these data, the amount of aluminum replaced by plastic was calculated for the residential replacement window market. For example, 2 million window frame units in 1985 with 15 pct growth compounded annually reaches 4 million units in 1990; 4 million units at 12 lb each equals the tonnage shown in table 2. Additional aluminum markets would be lost if plastics are improved for use in windows for commmercial and office buildings.

PACKAGING INDUSTRY

The U.S. packaging industry[19] is the one sector analyzed in this report where plastics are displacing significant amounts of glass as well as metals. This substitution is occurring primarily in the soft drink container market, which accounts for about one-third of all can and bottle demand. In the remainder of the packaging industry, plastics compete with other materials (e.g., paper and paperboard) in addition to metals and glass, as discussed below.

Packaging is the largest market for plastics, accounting for 12.7 billion lb or 28 pct of polymers sales in 1985 (*60*). However, these are virtually all "commodity" plastics having low unit value, so their total value in packaging may be less than that of the engineering plastics used in transportation, where only one-sixth as much of the material was sold this same year (*60*). For example, plastics for packaging may cost about $0.40 per pound, while those in automobiles cost several times as much ($1 to $2 per pound), and aircraft plastics are about 100 times as costly ($20 to $50 per pound).

Metal Cans

Seventy percent of all metal cans are for beverages and another 25 pct are for food. (Beverage cans are almost evenly divided between beer and soft drink use.) Until the 1950's, virtually all cans were made of tin-plated steel (the so-called "tin can"). Since that time, aluminum has made steady inroads, capturing 94 pct of the beverage can market from steel (*2*). The reverse percentages are true for food cans; i.e., steel retains 94 pct of this market and aluminum has the remaining 6 pct (*6*).

Since 1979, "cans and containers" has been aluminum's largest end use, in which it has several advantages over steel: (1) Aluminum cans are much lighter (about one-third the weight of steel cans), (2) they are seamless, unlike some steel cans that have welded or glued seams (soldered seams are being phased out), and (3) aluminum cans are easily recycled; in fact, more than half of this metal is reused.

In spite of these advantages, aluminum must overcome some technical problems before being used on a large scale in the food can market. In contrast to beverage use, where carbonation provides the necessary internal pressure to prevent collapse of aluminum cans, food cans, contain not such pressure (in fact, they have a vacuum). To prevent collapse, structurally strong aluminum food cans must be built with higher strength aluminum alloys and improved designs. One way of introducing internal pressure is to inject liquified nitrogen into the can just prior to sealing, where it warms up rapidly, evaporates, and produces gas pressure (*2*). Some in the can industry, especially executives in the aluminum industry, think these technical problems faced by aluminum food cans will be solved, thereby displacing steel in this market.

Although many in the container industry feel that beverage cans are a relatively secure market for aluminum, there are others who believe that plastic cans now being test-marketed for soft drinks will replace aluminum cans there. Despite the likely attraction of transparent plastic cans to consumers, these containers are more costly than aluminum cans and are not as easily recycled (*18*).

Can industry forecasts are less certain than those in the motor vehicle and aircraft industries, where composites (plastics) are more likely to continue replacing steel and aluminum, respectively. Producers in the can industry do not have a consensus on which materials will gain and which will lose market shares.

The metal can market is forecast to only grow about 1 pct/yr, paralleling the growth in population. Beverage cans are anticipated to grow at a higher rate (2 to 3 pct/yr) as the population has been increasing its consumption of soft drinks and correspondingly decreasing its use of coffee. Some think that this substitution of soft drinks for coffee has run its course, but others believe that added health concerns about coffee, higher coffee prices, etc., could mean further substitution (higher soft drink usage).

Partly offsetting this beverage can growth, the food can market is expected to decline slightly for several

[18]Each 100 ft^2 of metal residential siding uses approximately 45 lb of aluminum or 80 lb of steel (*17, 57*).

[19]The packaging industry has two basic types of products: (1) rigid containers (e.g., bottles and cans) and (2) flexible bags, wraps, and liners. Industry shipments in 1985 totaled $64 billion; nearly 40 pct of this was accounted for by paperboard (*59*).

reasons. These include reduced preparation of food at home due to smaller families and more working mothers; more use of frozen foods, partly because microwave ovens have increased the convenience of these foods by reducing their cooking time,[20] and larger consumption of food outside the home (*6*).

Bottles

Plastic bottles have made significant inroads into the soft drink market at the expense of glass because they have two advantages: plastic bottles are lighter in weight and far less susceptible to breakage than glass bottles. Both of these attributes reduce handling costs, and lighter weight also reduces fuel consumption costs in shipping.

The vast majority of plastic soft drink bottles used thus far have been in the 1- to 3-L size, and most of these were 2-L bottles. Smaller 16-oz and ½-L plastic bottles have been test-marketed in limited areas. The problem with these smaller bottles is loss of carbonation through the plastic wall (technically called inadequate "barrier properties" of the plastic), which reduces shelf life to an unacceptable level except in large cities, where quick turnover of inventory minimizes this problem (*6*).[21]

Glass bottle manufacturers are responding to the threat of substitution by using thinner glass-walled soft drink bottles covered with plastic foam in the 16-oz and ½-L sizes to reduce weight and breakage, respectively. These glass bottles are competitive, if not cheaper, in price, than similar size plastic bottles, and glass, unlike plastic, has no problem of inadequate barrier capabilities.

Also, traditional glass bottle makers have diversified into plastics. Owens-Illinois Inc., one of the largest and first to diversify of the glass container manufacturers, derives 25 pct of its sales from plastic containers (*23*). Kerr Glass Manufacturing Corp. also has entered the plastic container market (*18*).

Flexible Packaging

Flexible packaging includes plastic bags, liners, films, aluminum foil, paper, cardboard boxes, and combinations of these. It is the largest plastics-consuming category within the packaging sector, accounting for almost one-half of all plastics consumed in this market. The advent of the microwave oven has led to use of plastic dishes, trays, and lids for frozen foods at the expense of aluminum trays and foils. Consequently, the aluminum industry has been trying to develop a microwavable aluminum. In some cases the two materials are combined; for example, bags and "aseptic"[22] bottles are composed of aluminum foil laminated with plastic.

Drums

Drums are large steel, paperboard, cardboard, or plastic containers varying in capacity from 5 or 10 gal to more than 100 gal. Bulk chemicals are often shipped in drums, but chemicals in liquid form would generally not be sold or stored in the paperboard or cardboard type. These containers require much more steel, plastic, etc., per unit than smaller cans and bottles do, yet because far fewer of these drums are produced, the total quantity of material consumed in their manufacture is probably less than for cans and bottles. In this segment of the packaging market, drums composed of plastic increasingly are displacing those made of steel.

Substitution Among Different Types of Packaging

Some complications should be mentioned, although they can be difficult to analyze and/or quantify. Not only do aluminum and steel cans compete against each other and plastic bottles, but cans also substitute for glass bottles and jars, and all of these compete against paper containers (e.g., frozen juices in paper "tubes" or cans, frozen vegetables in cardboard boxes, etc.). Aseptic packages (see following discussion) compete as well, and plastic cans, should they prove commercial, will also compete. As a final example, plastic bags for frozen vegetables compete against paper boxes, steel food cans, and a relatively small quantity of glass jars. Therefore, while aluminum cans are the largest competitor of steel cans (and plastic bottles are the largest competitor of glass bottles), competition among all of these types of containers significantly complicates market forecasts. Moreover, customer preference for these container materials depends largely on consumer tastes that are not amenable to analysis.

New Developments

Polymer manufacturers are conducting R&D to try to solve the problem of carbonation loss from plastic containers by making the bottles up to eight layers thick (*7*). In addition, "aseptic" packages made of aluminum foil laminated with plastic are capable of keeping milk and fruit juices or drinks fresh for 6 months without refrigeration. Utilizing an "ultra-pasteurization" process from Sweden, these containers in small sizes (e.g. 8 oz) have been growing in popularity since their introduction several years ago in this country; in Europe, they have been available for many years.

In January 1986, Aluminum Co. of America (Alcoa) and Metal Box America, Inc., agreed to form a joint venture in the United States to develop and produce plastic food containers. About $100 million is to be invested in the venture over the first 3 yr, with each company having a 50-pct interest (*3*). Metal Box America is owned by Metal Box PLC, Britain's largest food, beverage, and aerosol container supplier. Improving the barrier capabilities of plastic packages to prevent loss of carbonation, infiltration of oxygen, and migration of moisture through the container wall has been under development by Metal Box (*3*). This is an example of Alcoa's strategy in recent years to diversify beyond aluminum to polymeric materials and thereby protect and/or increase its share of the packaging market should plastics displace aluminum. Thus, substitution of metal by plastics may represent opportunities as well as challenges to Alcoa.

Forecast Computations

Based on information compiled for this report, it is possible to estimate substitution of plastics for glass and

[20]Microwave ovens have also been responsible for the growing use of plastic dishes for frozen dinners at the expense of aluminum trays as discussed in the "Flexible Packaging" section below.

[21]This carbonation loss is only a minor problem for the 1-L size and virtually no problem for the larger size bottles.

[22]Aseptic packages are discussed below in the "New Developments" section.

metal in the rigid container sector of the packaging industry. In this sector, plastics compete with glass, metal (aluminum and steel), and paperboard primarily for use in bottles and cans. For this market it is estimated that plastics will displace approximately $386 million of glass containers and $223 million of metal containers in 1990. This displacement accounts for about 7 pct and 2 pct of the 1985 glass and metal container market, respectively.

In addition to the above forecast, estimates of substitution by plastics were made for the soft drink container market, the largest single market for plastic bottles. One-fifth of all plastic bottle and can shipments in 1985 were used in this market, where plastic competes primarily with glass and aluminum.[23]

The soft drink sector is one of the few rigid container markets predicted to grow appreciably, but it is expected to increase no more than 2 pct/yr through this decade (*7*). For the same period, the Department of Commerce estimates that plastic bottle production will increase 4 pct/yr, while metal can shipments will grow 1 pct/yr and glass bottle output will decline 0.5 pct/yr (*6*). Thus, it appears that most of the predicted plastics increase will erode glass and aluminum container markets rather than merely expand with growing soft drink demand. The estimated *maximum* amount of glass *or* aluminum that would be displaced by plastics in the soft drink market follows, in million short tons:

	1990	*1995*
Glass	7.8	10.9
Aluminum	.47	.66

The data shown for the forecast years are not cumulative.

The quantities shown for glass and aluminum displacement in the soft drink sector should not be combined to represent total substitution by plastic. Instead, each figure is intended to show only the maximum amount of glass or aluminum that would be displaced if each material alone was to compete with plastic. If current trends continue, glass will suffer more than aluminum in competition with plastic bottling. However, not enough information is available for a more precise differentiation among these competitors regarding substitution.

Different methods were used to make the preceding rigid container and soft drink market forecasts. For the rigid container forecast, Department of Commerce data on 1985 rigid container sales (*59*) and growth rates (*6*) were combined to estimate the value of glass and aluminum market shares that will be lost to plastics in 1990.[24] These calculations indicate that, by 1990, total bottle and can sales will reach $29 billion; and that the market share for plastic bottles will increase 2.1 pct as shares for glass and metal decline by 1.9 and 1.1 pct, respectively. Plastic accounted for 70 pct of all market share increases computed.[25] Thus, 70 pct of the market share losses for glass and metal are attributed to plastics growth. For example, the figure that represents market losses by glass between 1985 and 1990 equals 0.7 of 1.9 pct multiplied by $29 billion.

[23]Aluminum represented 94 pct of 1985 beverages can production; the remainder is accounted for by steel (*2*).

[24]Plastic bottle shipments in 1985 totaled about $4.3 billion (*59*). This value indicates, at least approximately, the magnitude of the market already lost by glass and metal.

[25]Paperboard represents the remaining growth.

The soft drink container forecast was developed by combining data that indicate the number of plastic bottles shipped in 1985, plastic container industry growth to 1990, forecasts of 1995 plastic bottle output, and the amount of glass or aluminum needed to match the total capacity of plastic bottles produced (*6-7, 15*). Forecast data indicate that shipments of 16-oz plastic beverage bottles will grow from 870 million units in 1985 to 8.0 billion units in 1995, while shipments of 1- to 3-L (primarily 2-L) plastic bottles will increase from 4.1 to 5.5 billion units during the same period (*15*). The 1995 estimates are based on the total container capacity of the plastic bottle figures for that year and the amounts of glass or aluminum needed to produce an equivalent number of bottles and/or cans.[26] For 1990, the same capacity equivalents were applied to 1985 plastic bottle shipments increased by the compound annual rate of 4 pct cited above. Before volume equivalents were computed, 1990 and 1995 plastic bottle estimates were reduced by 10 and 20 pct, respectively, to account for growth in the soft drink market (2 pct per year), which would mitigate the impact of substitution.

HEAVY MACHINERY AND EQUIPMENT PRODUCTION

The heavy machinery and equipment industry[27] consumed about 348 million lb of plastics yearly between 1980 and 1985, primarily to replace metals. Although a small portion of plastics substitute for rubber in hoses and gaskets, most polymer materials are used to manufacture parts such as casings, shields, instrument panels, and housings formerly made from steel, cast iron, or aluminum (*39*). The plastics are used to achieve lower costs based on lighter weight and ease of fabrication (*39*).

The total impact of substitution by plastics in this sector can be measured to some extent, but available information is not detailed enough to permit much differentiation among the types and quantities of metal displaced. As the chief rival of plastics in the industry, steel reportedly is the metal most affected by the substitution underway there. Based on the density of various materials used, it is estimated that every pound of plastic in the industry could displace about 4 lb of metal.[28] Thus, during 1985, plastics may have displaced approximately 700,000 st of metal in the machinery, equipment and tool industry. This quantity is relatively small compared with substitution by plastics in other industry sectors examined for this report. Nevertheless, the 0.7-million-st amount equals almost 7 pct of steel shipments for all machinery.

Neither the literature search nor the interviews conducted for this study yielded specific forecasts for plastic in the machinery and equipment industry. However, Department of Commerce estimates indicate that all but a few sectors of the industry will grow by

[26]Approximately 11.3 oz of glass or 0.6 oz of aluminum (*2*) is used to produce a 16-oz bottle or can. A 2-L bottle matches the capacity of 4.24 16-oz bottles and or cans.

[27]This sector encompasses producers of machinery, tools, and equipment for all industrial segments of the U.S. economy, including those examined in this report.

[28]The specific gravity of the most dense polymers used in the heavy machinery industry (reinforced thermosets) is approximately 2.0, while the average specific gravity for steels is about 7.8 (*38, 57, 60*). If the dimensional thickness of plastics used in the industry is much greater than that of the metals replaced, the ratio of these specific gravities should be correspondingly reduced.

about 3 to 7 pct annually through 1990 (*68*). Assuming that at least the minimum growth rate of 3 pct will prevail, average yearly consumption of plastic in the industry could increase to as much as 403 million lb in 1990. Using the steel-polymer density ratio noted above, this quantity of plastics equates to a displacement of 0.8 million st of metal.

SUMMARY AND CONCLUSIONS

The preceding analyses and the interviews with professionals in materials development and marketing indicate that advanced materials such as engineering polymers present dramatic challenges and opportunities for conventional nonfuel mineral producers. Substitution forecasts presented with the preceding analyses are summarized in table 3. Conclusions regarding these forecasts and key factors that will influence the emergence of advanced materials during the 1990's are discusssed below.

Table 3.—Summary of identified substitution by advanced plastic materials in five major U.S. industries[1]

Industrial sector	1985	1990	1995	2000
Motor vehicle manufacturing:				
Steel displaced by plastics ..... MMst ..	1.3	1.8-2.4	NI	2.7-7.3
Do .... pct ..	7-9	NI	NI	8-19
Passenger airliner manufacturing:[2]				
Aluminum displaced by polymer composites Mst ..	0.5	NI		4.0-11.0
Do .... pct ..	3	NI	NI	20-60
Building and construction:[3]				
Iron and steel displaced by plastics .. MMst ..	2.5	NI	4.3-6.1	NI
Do .... pct ..	9	NI	10-13	NI
Aluminum displaced by plastics .... Mst ..	37	NI	64	NI
Packaging (bottling and canning), MM$:				
Glass displaced by plastics	NI	386	NI	NI
Metal (Aluminum and steel) displaced by plastics	NI	223	NI	NI
Heavy machinery and equipment:				
Metal displaced by plastics .... Mst ..	700	800	NI	NI
Do .... pct ..	5	5	NI	NI

NI Not identified.
[1]See "Forecast Computations" portions of "Industry Analyses and Forecasts" section for an explanation of the estimates shown in this table. Data shown are not cumulative.
[2]Excludes military and private civil aircraft. For 1985, it is estimated that over 23,000 st of aluminum were displaced by plastic composites in the entire aerospace industry.
[3]Displacement in pipe, tube, siding, and window markets.

SUBSTITUTION FORECASTS

1. Plastics[29] have made the strongest competitive advances of all materials against metals and glass in many markets and will continue to do so in the 1990's. Calculations based on information obtained for this study indicate that at least one-fourth of all plastics and resins produced domestically compete directly with nonfuel mineral materials (table A-1). These computations do not include those markets where plastics compete with so many other materials in addition to nonfuel minerals that displacement of the latter could not be measured with sufficient precision. If these markets were added to the calculations of plastics use, the total probably would indicate that well over one-third of U.S. plastics production competes with metal and nonmetal minerals.

[29]See appendix for definitions and descriptions of advanced materials examined in this report.

2. As suggested by table 3, the 1990's will be a period of more intense competition between metals and polymers. Some automobile and aerospace executives believe that the outcome of this competition will determine which materials will be dominant within their industries in the 21st century. Steel and aluminum are the major metals most likely to be affected. Polymer materials already have replaced about 7 to 9 pct of the steel consumed in domestic motor vehicle production and may displace more than double that amount by the year 2000. In the construction industry, it is estimated that polymers have replaced slightly less than 10 pct of the iron and steel consumed, and by 1995 could displace up to 13 pct. In aerospace applications, polymer composites are displacing aluminum used for the "skin" of many new military aircraft and are expected to make large inroads in passenger airliner manufacturing during the next decade. Composites currently account for less than 3 pct of passenger airframe weight, but are forecast to account for as much as 65 pct during the 1990's (*66*). As a result, the proportion of passenger airframe weight composed of aluminum may decrease from the current 80 pct to as little as 20 pct by 2000.

The U.S. motor vehicle industry offers the greatest market potential for polymers by virtue of its demand for large volumes of steel that could be replaced by plastics. However, the outcome of materials competition in the industry is far from decided. An automobile executive contacted for this paper states that "steel still could be the 'high-tech material' of the future" (*4*). High-strength specialty steels coupled with new corrosion-resistant processes are being developed to complete more effectively with polymers in car and truck manufacturing. The wide forecast range shown for the year 2000 in table 3 reflects differences among experts interviewed about the degree of plastics substitution in the industry. If polymers can be developed for use as chassis parts (e.g., frames, wheels, and suspensions) as well as body panels, the upper end of the range shown in table 3 becomes more probable.

While the full extent of substitution by plastics is still debated in the motor vehicle industry, much greater use of reinforced polymers in the aerospace industry is virtually assured, at least in the military segment. This increased use appears inevitable for several reasons. First, for military aircraft, the primary goals of greater maneuverability, speed, and range are achieved most efficiently through weight reduction, and composites promise greater weight savings than any other material. Second, for all aircraft, the longer assembly line time and low unit output (as contrasted with mass-produced automobiles) is attuned to the longer curing and molding time required for polymer materials and parts. Finally, unlike their automotive counterparts, manufacturers of high-priced aircraft can more easily pass the greater costs of high-strength composites on to their customers.

3. As described in the preceding section, commercial use of advanced ceramics for nonelectrical purposes (principally as parts for motor vehicle engines) could

increase significantly during the 1990's, but these materials will not displace large quantities of metal in this century. Although ceramics are not expected to be used (except as coatings) in jet aircraft engines until well beyond the year 2000, they offer advantages that virtually ensure their eventual substitution for some quantity of critical metals and/or alloys in the aerospace industry.

CONDITIONS INFLUENCING SUBSTITUTION

1. Metal and glass producers have taken two approaches in response to strong competition from new materials: (1) increase R&D to improve competitiveness of current products, and (2) diversify production to include new materials. Examples among the first approach are the aluminum-lithium alloys developed to compete in the aerospace industry, and the new steels especially developed to match automobile manufacturing needs. Producers that have taken the second approach include a major U.S. glass container company that also produces plastic bottles, and domestic metal companies that have acquired high-tech materials firms or participate in joint production ventures with them. These latter companies are, in effect, wisely "hedging their bets" by seeking a strong market position regardless of which competing materials gain dominance.

2. New materials emerge first in those markets where superior performance properties rather than lower costs appear to be the principal consideration. Thus, advanced materials are prominent in high-tech industries (e.g., aerospace) where product performance criteria are so high that there is no alternative but to develop better materials despite initial costs. However, costs eventually determine both the pace and extent of the substitution process beyond the initial market. As increased output and production experience reduce unit costs, new materials become more competitive and can capture additional markets. At this point, it becomes very difficult for conventional materials producers to reverse the substitution trend and regain their original market shares.

3. The only relevant cost consideration in materials substitution today is the so-called "total package cost" (*30*). This cost includes not only the price of the material itself, but also all other costs involved in using the material to manufacture a product. Many new materials are priced higher than the conventional materials they displace. However, these new materials may be preferred because they offer the opportunity to reduce manufacturing costs sufficiently to offset their higher prices. For example, a one-piece plastic unit that replaces an item built from several parts could reduce assembly costs. Because total package costs are so important, materials producers now must work more closely with parts designers and other manufacturing system specialists to develop a product that is competitive.

4. Important considerations other than the intrinsic qualities of materials cost and performance also bear on the timing and rate of substitution. First, new materials must have a "proven track record"; i.e., firms are reluctant to incorporate a new material into their product until its performance record in other uses has proven reliability. Thus, superior performance in laboratory testing may be followed by years, or even decades, of observation (as in the aerospace industry where risks are high), before a new material is accepted as a substitute for a metal proven reliable by long use. Hesitancy to introduce a new material also results when a potential industrial user is not aware of all advantages offered by a new material, lacks assembly line experience with it, or would incur high retooling costs by converting to it. The cautious "wait and see" stance is an attitude that favors conventional materials already in place. It was observed in a diversity of industries regardless of whether the new material in question was for high-tech aerospace use or for common plumbing fixtures in the building trade.

Another condition (beyond materials cost and capability) that affects the intensity and pace of substitution is the status of the additional infrastructure needed to supply raw materials and tooling, distribute parts and equipment, and provide the training and expertise needed by manufacturers to fabricate their products from new materials. The establishment of such an infrastructure may take many years and can delay the commercial introduction of a new material long after what might be expected if one were to consider only the superior performance characteristics of the material relative to price.

5. The Federal Government exerts an important influence on advanced materials development through the individual research programs of its various agencies. These programs for advanced materials development total about $200 million annually (*69*) and entail funding for industry and university research as well as R&D by the Government itself.[30] In addition to funding and conducting research, the Federal Government can influence private sector materials development through its tax structure, antitrust requirements, incentives for capital investment, regulatory activities, and patent procedures. The combined impact of these activities on materials development and marketing is not clear, particularly given the new Federal tax reforms.

It is important to recognize that Federal materials research primarily is driven by priorities other than new materials development per se. Federal agencies fund materials research principally because existing materials do not meet the needs of their specific program goals. For example, Department of Defense requirements for low-weight weapons or long-range aircraft create demands for lighter materials that in turn lead to new materials research. Thus, new domestic materials industries in effect have become the unplanned "spinoffs" of related Government objectives.

One other aspect of Federal materials programs should be noted. Although each of these materials programs has individual objectives already judged to be in the national interest by the Executive Branch and Congress, it is clear that some of them have conflicting consequences; i.e., by supporting advanced materials R&D, the Government creates competitors for domestic mineral industries that also receive Government assistance. Perhaps this conflicting support ultimately produces improved materials through the rivalry it promotes. Nevertheless, Federal agencies should reexamine the net effects of their materials research very carefully and coordinate their efforts more closely to avoid major program conflicts.

6. The Federal Government may not have sufficient information to develop appropriate policies regarding the impact of advanced materials. New polymer industries,

[30]Funding for all Federal programs that directly or indirectly involve research on conventional materials as well as advanced materials may exceed $1 billion.

for example, are emerging and growing so rapidly that Government data collection has not been able to keep pace. Even basic data such as number of firms and establishments sometimes must be estimated. It is normal for information to lag behind developments in industries that typically are dynamic. However, projected growth rates for the advanced plastics and ceramics industries indicate that these sectors will become major, permanent market components that must be monitored effectively as interest in them expands and their economic and strategic importance increases.

7. The displacement of outmoded materials by superior substitutes is a recurring theme in the history of materials science. Thus, it can be argued that the competitive advances made by modern materials represent nothing more than the classic case of a substitute that cannot be deterred in the long run if it offers superior quality not otherwise available. Nevertheless, it is precisely the reach for higher quality, and thereby greater competitiveness, that motivates high-tech materials development and use. The resulting increase in competition has inflicted market losses on some conventional materials producers. However, as indicated by several industry executives interviewed, the net result, or so-called "bottom line," of high-tech substitution is that consumers can purchase better, lower cost products, and that U.S. manufacturers have more opportunities to be competitive in world markets.

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APPENDIX.—DEFINITIONS AND BACKGROUND DISCUSSION OF POLYMERS AND ADVANCED CERAMICS

Definitions of technical terms used in this report and a description of the new materials industries examined herein are presented below as background for the preceding analyses. For this study, the materials industry is defined as those commercial activities involved in the design and production of substances used for the fabrication of all manufactured products. This report is focused on two of the many new materials encompassed by the advanced materials industry: polymers and ceramics.

POLYMERS AND POLYMER-BASED COMPOSITES

Polymers, commonly known as "plastics" or "resins," are synthesized materials (usually organic) that can be molded at temperatures of only a few hundred degrees Fahrenheit and can retain a given shape when cooled. These materials are composed of large molecular chains that commonly link atoms of carbon, hydrogen, and oxygen, but also may contain other elements such as silicon, nitrogen, and fluorine. In the broadest sense, polymers include the more elastic rubbers. This paper, however, focuses on polymers and excludes rubbers.

Among the polymers are the commodity plastics (high-volume production, low unit value) and the engineering or high-performance plastics (low-volume production, high unit value). The engineering plastics have greater strength and/or can withstand significantly higher temperatures than the commodity plastics. Another classification of plastics are the thermoplastics and the thermosetting plastics or thermosets. Thermoplastics can be repeatedly softened and rehardened by raising and lowering the temperature, respectively; thermosets after hardening cannot be resoftened by increasing the temperature. Resins refer to organic liquids or solids that are themselves plastics and are the building blocks of more complex plastics compounds.

A composite refers to the combination of a matrix, or binding material, through which a different, reinforcing material is distributed. Although these two materials maintain separate identities, the composite formed by them exhibits properties superior to those of both. Metals, ceramics, and polymers are used to form the matrix and the reinforcing materials of various composites. This report is concerned with composites in which the matrix material is plastic, and in a few cases where the reinforcing material is plastic as well. The original and best known composite is fiberglass, consisting of glass reinforcing fibers and a plastic matrix.

Plastics recently have become the most widely used material in the United States. On a volume basis, their consumption now exceeds that of steel, copper, and aluminum combined. Although once perceived as a material only for cheap or shoddy goods, plastics have vastly improved during the past decade and have captured so many markets that they truly seem to be everywhere.

> Cars are constructed of it, and boats and even airplanes, to say nothing of computer housings and camera bodies and fishing rods and watch cases and suitcases and cookware and roller skates and toothpaste tubes. It has replaced the glass in our spectacles, the paper in our grocery bags, the wood in our tennis rackets, the cotton in our clothing . . . (etc). . . . (It is used) from outer space to the depths of the sea . . . (*14*)[1]

Table A-1 shows the markets for plastics sales in the United States during 1984 and highlights those sectors where it is reasonably certain that plastics substituted for metals and glass materials. Based on this table, it can be assumed that at least 24 pct of plastics sold in the United States currently are consumed in place of metals and glass (primarily in the packaging and motor vehicle industries). This is a conservative estimate because it does not include demand in markets where there is uncertainty about the types of material replaced by plastics (e.g., both wood and metal are competitors of plastic in furniture manufacturing). Analysis of each major market shown here with significant identified competition between plastics and metals or glass is provided in the analysis and conclusion sections of this report.

Table A-1.—Major U.S. markets with significant competition between plastics and metals or glass, 1985

Market	Plastics sales, MMlb	Sales replacing metals or glass, pct
Transportation	1,989	90
Building and construction	10,038	43
Packaging	12,774	17
Electrical and electronic	2,659	([1])
Furniture and furnishings	2,107	([1])
Industrial machinery	364	90
Consumer and institutional products	3,975	([1])
Adhesives, inks, coatings	2,142	([1])
Other	5,122	NA
Total or average[1]	41,170	24

NA Not available.
[1]For some industries so many additional materials (wood, paper, textiles) are competitors of plastics that no precise measure of market relationships between plastics and metals or glass could be developed. Therefore, the resulting 24-pct total share is a conservative estimate because it excludes markets where substitution by plastics is displacing unknown quantities of metals and glass.

Although the first synthetic plastics date back to the 1860's in the United States (and to the 1850's in Europe), the most important U.S. developments in polymer science have occurred in this century (*60*). The commercial development of today's modern thermoplastics (polyvinyl chloride, polyethylene, polystyrene, etc.) began in the 1930's (*60*). Shortages during World War II led to increased demand for plastics as substitutes for materials (such as natural rubber) and promoted polymer research (*60*). During the next decade, large-scale production of plastics reduced their costs dramatically and they began to compete with traditional materials such as wood, paper, metal, and glass. Production rates stagnated in the late 1960's, but there has been a resurgence of the plastics industry during recent years due to rapid advances in polymer technology, particularly the development of polymer blends (analogous to alloys) with properties vastly superior to those of their individual constituents (*61*). Thus, plastics producers believe that they are entering a new period of rapid growth. Studies indicate that average annual growth in domestic sales of plastics will be about 3 to 5 pct to 1990 and 4 pct thereafter to 1995

[1]Underlined numbers in parentheses refer to items in the list of references preceding this appendix.

(*5, 49*). However, growth rates as high as 25 pct/yr are forecast in the 1990's for certain types of high-performance polymers, such as reinforced plastics and composites (*12, 22*).

Today, the plastics industry (SIC 2821 and 3079) is comprised of more than 10,000 firms throughout the United States with over 650,000 employees producing resins, machinery, fabricated products, and molds (*5*). Well over 10,000 varieties of plastic are marketed domestically (*14*). Prices for these materials range from less than a dollar per pound to hundreds and even thousands of dollars per pound for more exotic composites needed by the aerospace industry. The average price for all plastics produced in 1984 was 43 cents per pound (*60*). The value of industry shipments during that year was over $40 billion. About half of this production was accounted for by the six largest U.S. plastics producers (Dow Chemical, Du Pont, Exxon, Mobil Oil, Union Carbide, and Amoco) (*60*).

Oil and chemical corporations lead the list of major domestic producers because the principal raw materials for plastics are petrochemicals (ethylene, propylene, and benzene) derived from petroleum. Petroleum will continue to be the source of nonfuel plastic feedstocks even after its use as a fuel begins to decline (*42*). In fact, oil and feedstock import dependence is an important concern for the U.S. polymer industry. Well into the future, other sources of carbon compounds for polymers, particularly coal, may replace petroleum; still later, plant matter may be converted into plastics. Most of the necessary conversion technology already exists for coal but not for vegetable matter. The economic feasibility of such conversion systems would depend on the scarcity of petroleum as plastics demand increases.

The plastics industry also uses appreciable amounts of nonfuel industrial minerals as fillers, extenders, pigments and reinforcing agents in polymers and resins. These minerals include talc, mica, feldspar, boron, soda ash, and glass sand. Although their use is a boon for some producers, these minerals account for less than 5 pct of polymer materials, by weight.

ADVANCED CERAMICS

Ceramics are materials composed of inorganic, nonmetallic powdered compounds that have been consolidated by the application of high-temperature heat (*65*). These compounds commonly include silicon and alumina, but the high-technology ceramics examined in this study can be composed of boron carbide, silicon carbide, silicon nitride, beryllium oxide, magnesium oxide (often in combination with other oxides), nonmetallic magnetics, and ferroelectrics (*69*).

Advanced ceramics are low-volume, high-unit-value products that have been developed only during the last 30 yr. These new materials are unlike the common high-volume, low-unit-value ceramic products of clay, glass, brick and tile produced since ancient times. Advanced ceramics are valued for their thermal, wear, and corrosion resistance; electrical insulation properties; high magnetic permeability; and special optical features (fiber optics is a ceramic). These characteristics make advanced ceramics potentially invaluable for use in high-performance engines, machines, other devices, and electronic components. Much of the attention given to advanced ceramics in recent years concerns its potential for use in automobile engines. Eventually these ceramics could act as substitutes for cobalt and other critically needed metals in jet aircraft engines, and thereby help reduce U.S. dependence on strategic material imports (*65*).

Unfortunately, the chemical structure that provides the superior properties cited above also imparts undesirable attributes, especially extreme brittleness that can cause shattering with little or no warning. Moreover, the costly and labor-intensive techniques used to fabricate advanced ceramic products make them relatively expensive. Consequently, substantial research is still necessary before the inherent problems of ceramics will allow significant replacement of metals.

The advanced ceramics industry currently encompasses two principal activities—the production of electronic components and the production of engineering products and parts. Together, these two businesses had markets totaling an estimated $5.1 billion in 1986 (*65*). At least 50 major U.S. firms are engaged in each activity (*65*).

Some documented forecasts of demand for advanced ceramics are available. Future demand will depend considerably on the degree of substitution that ceramics attains in end uses such as electronics, cutting tools, and heat engines. In a 1984 report, the Department of Commerce estimated the projected shipments of advanced ceramics shown in table A-2.

Table A-2.—Projected U.S. shipments of advanced ceramics, by end use (1980 dollars) (65)

End use	1980		1990		2000	
	MM$	pct	MM$	pct	MM$	pct
Electronics	534	89	1,900	75	3,485	59
Cutting tools	45	7.5	380	15	960	16
Wear parts	20	3	180	7	540	9
Heat engines	0	0	56	2	840	15
Other	2	0.5	15	1	70	1
Total	601	100	2,531	100	5,895	100

Discussions of expected applications for advanced ceramics within specific industrial sectors are provided in the "Industry Analyses and Forecasts" section of the main text.

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